[Technical Paper]

Compact Dual-band BPF Composed of LC J -inverters Using Lumped Elements

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Abstract

A compact dual-band bandpass filter (DB-BPF) composed of chip and patterned lumped elements is realized. Two types of dual-band LC J -inverters are proposed for DB-BPF design. Also, a large amount of attenuation between two BPF characteristics is realized by the effects of the proposed dual-band LC J -inverters. The fabricated DB-BPF has both good isolation characteristics and compact size.

Keywords: Dual-band bandpass filter (DB-BPF), Compact DB-BPF, DB-BPF synthesis, Lumped element, Dual-band LC J -inverter

1. Introduction

In wireless communication systems, as the amount of data being communicated is larger, more frequency bands or broader frequency bandwidth are required. A carrier aggregation (CA) technique has been used for acquiring broad frequency bandwidth in rare frequency environments. Although many bandpass filters (BPFs) and switches have been used in wireless communication devices for realizing the CA technique, the sizes of them are predicted to reach their limit.

A compact dual-band bandpass filter (DB-BPF) is an effective circuit for downsizing radio frequency (RF) frontends. Significant research has been done for compact DB-BPFs; however, there have been few studies in which the DB-BPFs have both high isolation characteristics between two channels and compact size. Compact DB-BPFs with high isolation characteristics using spiral-shaped stepped impedance resonators (SIRs)[1] and folded SIRs[2] are shown. It has been found that SIR is a key technology for satisfying the need for both the isolation characteristic and compact size; though, in order to be more miniaturized, it is necessary to consider other resonator candidates. Microstrip line (MSL) and coplanar waveguide (CPW) types of compact spiral resonators are employed for DB-BPFs[3] however, they are difficult to use, with the exception of a superconductor material, because a multi-turned

spiral resonator composed of thin conductor lines causes high insertion loss. Recently, a dual-band matching network using lumped elements for DB-BPF design is shown. [4] This approach satisfied the need for both low insertion loss and a downsized circuit area. Chip or other types of lumped elements are good candidates for realizing a compact DB-BPF if higher isolation characteristics are achieved.

In this paper, we attempt to realize a compact DB-BPF with high isolation characteristics between two BPF characteristics using lumped elements. First, synthesis of the DB-BPF is explained. We propose new J -inverters which are composed of lumped elements and operate in two frequency bands. Next, the circuit structure is configured using chip and copper-foil-patterned lumped elements. Finally, the measured frequency characteristics of the fabricated DB-BPF are shown.

2. Circuit Synthesis of DB-BPF

Figure 1 shows a flow chart for DB-BPF design. Although it is similar to the general DB-BPF design procedure, our results are characterized by the elements taken from J -inverters and circuit structure designs.

There are many synthesis methods for DB-BPFs based on a coupling matrix[4–11] or K - or J -inverters.[12–15] Those are excellent methods when a DB-BPF structure is configured using series or parallel resonators, external quality factor Q_e and coupling coefficient k_{ij} ($i, j = 1$ to N),

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Fig. 1 Flow chart for DB-BPF design.

where N shows the number of resonators; however, this is not always good in cases with a DB-BPF design using chip or patterned lumped elements. A DB-BPF made by lumped elements must directly transform a prototype lowpass filter (LPF) into the DB-BPF. The following frequency transformation equation for a multi-band BPF is proposed:[16]

$$\Omega = \frac{\omega}{A_1} - \frac{B_1}{\omega} - \sum_{i=2}^M \frac{1}{\frac{\omega}{A_i} - \frac{B_i}{\omega}}. \quad (1)$$

Especially for $M = 2$, namely DB-BPF (M means the number of passbands),

$$\Omega = \frac{\omega}{A_1} - \frac{B_1}{\omega} - \frac{1}{\frac{\omega}{A_2} - \frac{B_2}{\omega}}, \quad (2)$$

where Ω and ω show the angular frequency for a prototype DB-BPF and the real angular frequency for a DB-BPF, respectively. The prototype DB-BPF is based on a prototype LPF.[17] In the case of the prototype LPF, the prototype angular frequencies of a passband, a cutoff and a rejection band are $0 \leq \Omega \leq 1$, $\Omega = 1$ and $\Omega > 1$, respectively. Also, A_1 , B_1 , A_2 and B_2 show the unknown constants and can be solved for by considering four boundary conditions for a DB-BPF.

The relationships among Ω , ω_1 , ω_2 , ω_3 and ω_4 ($\omega_1 < \omega_2 < \omega_3 < \omega_4$) are as follows:

$$\Omega = -1 = \frac{\omega_1}{A_1} - \frac{B_1}{\omega_1} - \frac{1}{\frac{\omega_1}{A_2} - \frac{B_2}{\omega_1}} \quad (3)$$

$$\Omega = 1 = \frac{\omega_2}{A_1} - \frac{B_1}{\omega_2} - \frac{1}{\frac{\omega_2}{A_2} - \frac{B_2}{\omega_2}} \quad (4)$$

$$\Omega = -1 = \frac{\omega_3}{A_1} - \frac{B_1}{\omega_3} - \frac{1}{\frac{\omega_3}{A_2} - \frac{B_2}{\omega_3}} \quad (5)$$

$$\Omega = 1 = \frac{\omega_4}{A_1} - \frac{B_1}{\omega_4} - \frac{1}{\frac{\omega_4}{A_2} - \frac{B_2}{\omega_4}} \quad (6)$$

where ω_1 , ω_2 , ω_3 and ω_4 show the desired edge angular frequencies for each BPF. In the case of the Chebyshev type, those are defined as two edge angular frequencies, which are equal to the passband ripple of $|S_{21}|$. While, in the case of the Butterworth type, those are shown to be two edge angular frequencies, which are equal to 3 dB degrading from maximum $|S_{21}|$. When Eqs. (3) to (6) are solved for A_1 , B_1 , A_2 and B_2 , those are shown as follows:

$$A_1 = \omega_2 - \omega_1 + \omega_4 - \omega_3, \quad (7)$$

$$B_1 = \frac{\omega_1 \omega_2 \omega_3 \omega_4}{\omega_1 \omega_2 (\omega_4 - \omega_3) + \omega_3 \omega_4 (\omega_2 - \omega_1)}, \quad (8)$$

$$A_2 = \frac{(\omega_2 - \omega_3)(\omega_4 - \omega_3)(\omega_2 + \omega_4)(\omega_1 + \omega_3)}{\{\omega_1 \omega_2 (\omega_4 - \omega_3) + \omega_3 \omega_4 (\omega_2 - \omega_1)\} (\omega_2 - \omega_1 + \omega_4 - \omega_3)^2}, \quad (9)$$

$$B_2 = \frac{\{\omega_1\omega_2(\omega_4-\omega_3)+\omega_3\omega_4(\omega_2-\omega_1)\}^2}{(\omega_2-\omega_3)(\omega_4-\omega_3)(\omega_2+\omega_4)(\omega_1+\omega_3)} \frac{(\omega_2-\omega_1+\omega_4-\omega_3)}{(\omega_1-\omega_2)(\omega_4-\omega_1)}. \quad (10)$$

Figures 2 and 3 show the relationship between the elements for prototype LPF and DB-BPF resonators. g_L , g_C , Z_0 and G_0 show inductive and capacitive g -parameters of the prototype LPF,[17] impedance and admittance, which are normally 50 Ω and 0.02 S, in the filter. Figure 4 shows the circuit schematic of a third-order DB-BPF. The values of each inductor and capacitor in Fig. 4 are calculated as:

$$Z_{in} = Z_{out} = \frac{1}{G_{in}} = \frac{1}{G_{out}}, \quad (11)$$

$$L_{S11} = L_{S31} = \frac{g_L Z_0}{A_1}, \quad (12)$$

$$C_{S11} = C_{S31} = \frac{1}{B_1 g_L Z_0}, \quad (13)$$

Fig. 2 An inductor for prototype LPF and dual-band resonators.

Fig. 3 A capacitor for prototype LPF and dual-band resonators.

Fig. 4 Circuit schematic of a third-order DB-BPF.

$$L_{S12} = L_{S32} = \frac{g_L Z_0}{B_2}, \quad (14)$$

$$C_{S12} = C_{S32} = \frac{1}{A_2 g_L Z_0}, \quad (15)$$

$$L_{P21} = \frac{1}{B_1 g_C G_0}, \quad (16)$$

$$C_{P21} = \frac{g_C G_0}{A_1}, \quad (17)$$

$$L_{P22} = \frac{1}{A_2 g_C G_0}, \quad (18)$$

$$C_{P22} = \frac{g_C G_0}{B_1}. \quad (19)$$

3. Dual-band LC J -inverters

When a printed circuit board (PCB) made of two copper foil layers is employed for configuring a lumped element-type DB-BPF, the circuit size is large, caused by the arrangement of the series LC resonators, which are L_{S11} , C_{S11} , L_{S31} and C_{S11} , shown in Fig. 4. Therefore, it is necessary to transform the circuit using K - or J -inverters. Normal K - and J -inverters work as impedance and admittance inverters. For example, a series-connected inductor which is sandwiched by two K - or J -inverters changes to a parallel-connected capacitor [17, pp. 113–128]. In contrast, a parallel-connected inductor changes to series-connected capacitor. However, normal K - or J -inverters cannot be used for transformation of a lumped element-type DB-BPF because those are for a single-band BPF. Therefore, two types of dual-band J -inverters are proposed.

3.1 Dual-band LC J -inverter between dual-band resonators

Figure 5 shows a dual-band LC J -inverter between dual-band resonators. A dual-band LC K -inverter can also introduce using same concept by considering impedances between them. L_{inv} and C_{inv} show the inductance and capacitance in the dual-band LC J -inverter, which is defined as type 1. First, ω_{r1} and ω_{r2} ($\omega_{r1} < \omega_{r2}$) are calculated by

Fig. 5 Dual-band LC J -inverter (type 1).

solving the following equations:

$$J = \pm \left(\omega C_{inv} - \frac{1}{\omega L_{inv}} \right), \quad (20)$$

$$\omega_{r1} = \frac{-JL_{inv} + \sqrt{(JL_{inv})^2 + 4L_{inv}C_{inv}}}{2C_{inv}L_{inv}}, \quad (21)$$

$$\omega_{r2} = \frac{JL_{inv} + \sqrt{(JL_{inv})^2 + 4L_{inv}C_{inv}}}{2C_{inv}L_{inv}}, \quad (22)$$

$$\omega_0 = \sqrt{\omega_{r1}\omega_{r2}}. \quad (23)$$

Next, from solving Eqs. (21), (22) and (23),

$$C_{inv} = \frac{J}{\omega_{r2} - \omega_{r1}}, \quad (24)$$

$$L_{inv} = \frac{\omega_{r2} - \omega_{r1}}{\omega_0^2 J}. \quad (25)$$

ω_{r1} and ω_{r2} are consistent with $\sqrt{\omega_1\omega_2}$ and $\sqrt{\omega_3\omega_4}$ when a DB-BPF is designed.

3.2 Dual-band LC J-inverter between a dual-band resonator and input or output load

The frequency characteristics in a case where a dual-band LC J-inverter is placed between Z_{in} or Z_{out} and a dual-band resonator, as shown in Fig. 5, are degraded. Thus, another type of dual-band LC J-inverter is proposed. Figure 6 shows a dual-band LC J-inverter, defined as type 2, which is placed between a dual-band resonator and an input or output load. A dual-band LC K-inverter can also introduce using same concept by considering impedances between them.

L_{p1inv} , L_{p2inv} , C_{p1inv} and C_{p2inv} show the inductances and capacitances, respectively, in the type 2 dual-band LC J-inverter. First, ω_{i1} and ω_{i2} ($\omega_{i1} < \omega_{i2}$) are calculated by solving the following equations:

$$Y_{p1inv}(\omega) = j\omega C_{p1inv} + \frac{1}{j\omega L_{p1inv}}, \quad (26)$$

$$Y_{p2inv}(\omega) = -j\omega C_{p2inv} - \frac{1}{j\omega L_{p2inv}}. \quad (27)$$

Introducing input admittance Y_{in} from the right side of Fig. 6,

Fig. 6 Dual-band LC J-inverter (type 2).

$$Y_{in} = Y_{p2inv} + \frac{GY_{p1inv}}{Y_{p1inv} + G} = \frac{G(Y_{p1inv} + Y_{p2inv}) + Y_{p1inv}Y_{p2inv}}{Y_{p1inv} + G}, \quad (28)$$

Considering the relationship between Y_{in} and the J-inverter,

$$Y_{in} = \frac{J^2}{G_{in}}. \quad (29)$$

Also, using the conditions of $Re[Y_{in}] = J^2/G_{in}$ and $Im[Y_{in}] = 0$,

$$Re \left\{ \frac{G(Y_{p1inv} + Y_{p2inv}) + Y_{p1inv}Y_{p2inv}}{Y_{p1inv} + G} \right\} = \frac{J^2}{G_{in}}, \quad (30)$$

$$Im \left\{ \frac{G(Y_{p1inv} + Y_{p2inv}) + Y_{p1inv}Y_{p2inv}}{Y_{p1inv} + G} \right\} = 0. \quad (31)$$

Solving Eqs. (30) and (31) for ω ,

$$\omega_{i1} = \frac{-\frac{D}{C_{p1inv}} + \sqrt{\left(\frac{D}{C_{p1inv}}\right)^2 + \frac{4}{L_{p1inv}C_{p1inv}}}}{2}, \quad (32)$$

$$\omega_{i2} = \frac{\frac{D}{C_{p1inv}} + \sqrt{\left(\frac{D}{C_{p1inv}}\right)^2 + \frac{4}{L_{p1inv}C_{p1inv}}}}{2}. \quad (33)$$

ω_{i1} and ω_{i2} are consistent with $\sqrt{\omega_1\omega_2}$ and $\sqrt{\omega_3\omega_4}$ when a DB-BPF is designed.

Here,

$$D = \sqrt{\frac{G_{in}^2 J^2}{G_{in}^2 - J^2}} (\because G > J). \quad (34)$$

Finally, solving Eqs. (32) and (33) for L_{p1inv} , C_{p1inv} , L_{p2inv} and C_{p2inv} ,

$$L_{p1inv} = \frac{\omega_{i2} - \omega_{i1}}{D\omega_{i2}\omega_{i1}}, \quad (35)$$

$$C_{p1inv} = \frac{D}{\omega_{i2} - \omega_{i1}}, \quad (36)$$

$$L_{p2inv} = \frac{\omega_{i2} - \omega_{i1}}{F\omega_{i2}\omega_{i1}}, \quad (37)$$

$$C_{p2inv} = \frac{F}{\omega_{i2} - \omega_{i1}}, \quad (38)$$

$$\therefore F = \frac{G_{in}^2 D}{G_{in}^2 + D^2}. \quad (39)$$

4. Circuit Design of DB-BPF

Table 1 shows the design specifications for a DB-BPF. The DB-BPF design is based on the method shown in section 3. Tables 2 and 3 show the values calculated from Eqs. (7) to (19). Figure 7 shows the calculated frequency characteristics from a circuit simulator. Advanced Design System (ADS) is used as the circuit simulator. Also, a transformed circuit using dual-band LC J-inverters and circuit

Table 1 Design specifications.

Parameter	low-band	high-band
Center frequency (GHz)	2.399	5.194
Fractional bandwidth FBW	0.05	0.1
Passband ripple (dB)	< 0.1	< 0.1

Table 2 Calculated values from Eqs. (7)–(10).

Parameter	Value
ω_1 (rad/s)	1.470×10^{10} (2.34 GHz)
ω_2 (rad/s)	1.546×10^{10} (2.46 GHz)
ω_3 (rad/s)	3.104×10^{10} (4.94 GHz)
ω_4 (rad/s)	3.431×10^{10} (5.46 GHz)
ω_0 (rad/s)	2.218×10^{10} (3.53 GHz)
A_1 (rad/s)	3.431×10^9
B_1 (rad/s)	1.565×10^{11}
A_2 (rad/s)	6.855×10^{10}
B_2 (rad/s)	4.021×10^9

Table 3 Circuit elements in Fig. 4.

Parameter	Value
$Z_{in} = Z_{out}$ (Ω)	50
$L_{s11} = L_{s31}$ (nH)	12.83
$C_{s11} = C_{s31}$ (pF)	0.1238
$L_{s12} = L_{s32}$ (nH)	9.2
$C_{s12} = C_{s32}$ (pF)	0.2828
L_{p21} (nH)	0.2783
C_{p21} (pF)	5.707
L_{p22} (nH)	0.6357
C_{p22} (pF)	4.093

element values are shown in Fig. 8 and Table 4, respectively. The values of all J -inverters are equal to 0.01 S. L_{p11} , C_{p11} , L_{p12} , C_{p12} , L_{p31} , C_{p31} , L_{p32} and C_{p32} show transformed circuit elements by J -inverters. Figure 9 shows the frequency characteristics for the transformed circuits. L_{p1inv} , C_{p1inv} , L_{p2inv} and C_{p2inv} are calculated using Eqs. (35) to (39). A transmission zero around 3.54 GHz appears as a result of the dual-band LC J -inverters. Consequently, a large amount of attenuation at ω_0 , which is more than 200 dB, is acquired. In the next section, a circuit structure and simulated results from an electromagnetic simulator are shown.

Fig. 7 Frequency characteristics of a third-order DB-BPF for Fig. 4.

Fig. 8 Transformed third-order DB-BPF using dual-band LC J -inverters.

Table 4 Circuit elements in Fig. 8.

Parameter	Value
$Z_{in} = Z_{out}$ (Ω)	50
L_{p1inv} (nH)	3.092
C_{p1inv} (pF)	0.6563
$L'_{p11} = L'_{p31}$ (nH)	3.508
$C'_{p11} = C'_{p31}$ (pF)	0.222
$L'_{p12} = L'_{p32}$ (nH)	2.828
$C'_{p12} = C'_{p32}$ (pF)	0.92
L_{inv} (nH)	3.571
C_{inv} (pF)	0.5684
L'_{p21} (nH)	0.3297
C'_{p21} (pF)	4.57
L'_{p22} (nH)	0.6357
C'_{p22} (pF)	4.093

Fig. 9 Frequency characteristics of a third-order DB-BPF for Fig. 8.

Fig. 10 Circuit structure of a third-order DB-BPF.

5. Circuit Structure of DB-BPF Using Chip Lumped Elements

Figure 10 shows a first circuit structure of a DB-BPF. A microstrip line (MSL) structure is assumed. The DB-BPF is configured using chip and copper-foil-patterned lumped elements. Table 5 shows the lumped elements for configuring the DB-BPF. The inductors form by high impedance copper foil patterns, since this DB-BPF is strongly affected by the sensitivities of inductors. The relative dielectric constant ϵ_r , $\tan\delta$ and the thickness of the dielectric substrate are 3.2, 0.001, and 0.5 mm, respectively. Also, the conductivity and thickness of the conductor are 5.8×10^7 S/m and 18 μm , respectively. The size of the chip capacitor is equal to 0.5×1.0 mm. GJM1555C series chip capacitors made by Murata Manufacturing Co., Ltd. were selected.[18]

Table 5 Explanation of circuit elements in Fig. 10.

Parameter	Model number or type	Value or total length
L_{p1inv} (nH)	pattern (width = 0.1 mm)	5.4 mm
L'_{p11} $= L'_{p31}$ (nH)	pattern (width = 0.1 mm)	4.05 mm
L'_{p12} $= L'_{p32}$ (nH)	pattern (width = 0.1 mm)	4.05 mm
L_{inv} (nH)	pattern (width = 0.1 mm)	5.4 mm
L'_{p21} (nH)	pattern (width = 0.1 mm)	0.6 mm
L'_{p22} (nH)	via pin and ESL of C'_{p21}	—
C_{p1inv} (pF)	GJM1555C1HR60WB01D	0.6 ± 0.05 pF
C'_{p11} $= C'_{p31}$ (pF)	GJM1555C1HR10WB01D	0.1 ± 0.05 pF
C'_{p12} $= C'_{p32}$ (pF)	GJM1555C1HR90WB01D	0.9 ± 0.05 pF
C_{inv} (pF)	GJM1555C1HR30WB01D	0.3 ± 0.05 pF
	GJM1555C1HR30WB01D	0.3 ± 0.05 pF
C'_{p21} (pF)	GJM1555C1H3R8BB01D	3.8 ± 0.1 pF
C'_{p22} (pF)	GJM1555C1HR30WB01D	0.3 ± 0.05 pF
	GJM1555C1HR30WB01D	0.3 ± 0.05 pF
	GJM1555C1HR30WB01D	0.3 ± 0.05 pF

Fig. 11 Frequency characteristics of Fig. 10.

S-parameter data in Touchstone formats for chip capacitors are employed when the DB-BPF are configured using an electromagnetic (EM) simulator. The frequency characteristics calculated by the EM simulator are shown in Fig. 11. Sonnet is used for the EM simulator. Those results are degraded compared with those from circuit simulation. The causes are unwanted parasitic inductances and capacitances from land patterns and chip elements. These parasitic elements are compensated, since it is difficult to remove them. As trial and error, it is found that influences of L'_{p11} (L'_{p31}), L'_{p12} (L'_{p32}) and C'_{p12} (C'_{p32}) against frequency characteristics of Fig. 11 are dominant. It is necessary to optimize them by increasing total lengths of L'_{p11} (L'_{p31})

Fig. 12 Circuit structure after optimizing Fig. 10.

Table 6 Explanation of circuit elements in Fig. 12.

Parameter	Model number or type	Value or total length
L_{p1inv} (nH)	pattern (width = 0.1 mm)	5.4 mm
L'_{p11} = L'_{p31} (nH)	pattern (width = 0.1 mm)	1.9 mm
L'_{p12} = L'_{p32} (nH)	pattern (width = 0.1 mm)	3.5 mm
L_{inv} (nH)	pattern (width = 0.1 mm)	5.4 mm
L'_{p21} (nH)	pattern (width = 0.1 mm)	0.6 mm
L'_{p22} (nH)	via pin and ESL of C'_{p21}	–
C_{p1inv} (pF)	GJM1555C1HR60WB01D	0.6 ± 0.05 pF
C'_{p11} = C'_{p31} (pF)	GJM1555C1HR10WB01D	0.1 ± 0.05 pF
C'_{p12} = C'_{p32} (pF)	GJM1555C1HR80WB01D	0.8 ± 0.05 pF
C_{inv} (pF)	GJM1555C1HR30WB01D	0.3 ± 0.05 pF
	GJM1555C1HR30WB01D	0.3 ± 0.05 pF
C'_{p21} (pF)	GJM1555C1H3R8BB01D	3.8 ± 0.1 pF
C'_{p22} (pF)	GJM1555C1HR30WB01D	0.3 ± 0.05 pF
	GJM1555C1HR30WB01D	0.3 ± 0.05 pF
	GJM1555C1HR30WB01D	0.3 ± 0.05 pF

and L'_{p12} (L'_{p32}) and the capacitance of C'_{p12} (C'_{p32}). Figure 12 and Table 6 show the optimized circuit structure and the parameters of the DB-BPF. The EM simulated results in Fig. 13 are almost in good agreement with those from circuit simulation.

Fig. 13 EM simulated frequency characteristics shown in Fig. 12.

Fig. 14 Photograph of a fabricated third-order DB-BPF.

Fig. 15 Measured frequency characteristics of a fabricated third-order DB-BPF.

6. Fabrication and Measurement of DB-BPF Using Chip Lumped Elements

Figure 14 shows a photograph of the fabricated DB-BPF. Copper foil patterns are fabricated using a PCB prototyping machine. After its process, chip capacitors and SMA connectors are soldered by hand. Figures 15 and 16 show the measured frequency characteristics. Also, Table 7

Fig. 16 Expanded frequency characteristics around passbands of Fig. 15.

Table 7 Comparison with frequency characteristics.

Parameter	Circuit simulation		Measured results	
	low-band	high-band	low-band	high-band
Center frequency (GHz)	2.4	5.19	2.4	5.15
<i>FBW</i>	0.05	0.1	0.069 (3 dB <i>BW</i>)	0.131 (3 dB <i>BW</i>)
Insertion loss (dB)	lossless	lossless	4.2	2.1
Return loss (dB)	16.9	17.3	12.2	8

Table 8 Benchmarking of DB-BPF.

Ref.	Center frequency (GHz)		Center frequency of DB-BPF (GHz)	<i>FBW</i>		Insertion loss (dB)		Maximum isolation (dB)	40-dB isolation bandwidth (GHz)	40-dB isolation <i>FBW</i>	Normalized area by λ_g^2
	low-band	high-band		low-band	high-band	low-band	high-band				
[1]	1.58	2.4	1.944	0.06	0.038	1.1	1.1	55	0.208	0.107	0.175
[2]	1.57	5.2	2.857	0.034	0.099	1.78	1.39	65.2	1.904	0.666	0.014
[3]	1.8	2.4	2.078	0.059	0.04	0.1	0.13	>75	0.343	0.165	0.008
[7]	2.43	5.26	3.575	0.123	0.057	1.86	3.42	52	1.030	0.288	0.008
[13]	20.0	21.0	20.5	0.015	0.014	1.37	1.1	59	0.163	0.008	1.158
[14]	1.05	1.29	1.168	0.066	0.056	1.48	1.35	50.6	0.022	0.019	0.166
[15]	1.85	2.85	2.296	0.119	0.074	1.2	2.1	45.5	0.055	0.024	0.096
[19]	0.924	1.79	1.287	0.097	0.153	2.4	1.92	55	0.062	0.048	0.014
[20]	2.45	5.7	3.737	0.107	0.062	1	1.2	55.5	0.304	0.081	0.004
[21]	2.43	5.26	3.575	0.123	0.057	1.86	3.42	52	1.03	0.288	0.008
[22]	0.61	1.36	0.911	0.323	0.105	0.45	0.75	60	0.195	0.214	0.011
[23]	0.9	1.75	1.255	0.42	0.15	0.2	0.5	48	0.069	0.055	0.022
[24]	2.37	29.84	8.410	0.194	0.065	0.75	1.74	23	24.97 (23-dB isolation)	2.969	0.074
[25]	8	11.4	9.550	0.030	0.025	2.26	3.07	>50	2.396	0.251	2.175
[26]	13.7	19.1	16.17	0.023	0.022	3.5	3.1	58	3.440	0.213	1.184
This work	2.4	5.15	3.516	0.069	0.131	4.2	2.1	73.5	1.837	0.522	0.022

shows a comparison between the design specifications and EM simulated results. Although the return loss is worse than that from circuit simulation, because of the tolerances of lumped elements, dual-band characteristics are acquired. Insertion losses are calculated by circuit simulation considering the equivalent series resistances (ESRs) of each inductor and capacitor. Those are almost in good agreement with the measured ones. The physical size is $11.45 \times 12 \text{ mm}^2$. The normalized size by guided wavelength λ_g at the center frequency of 2.4 GHz in the low band is $0.146 \times 0.153 \lambda_g^2$.

Table 8 shows benchmarking of the DB-BPF. From a technical point of view for a DB-BPF, the isolation characteristics mean the amount of attenuation between two BPF characteristics. The parameters of 40-dB isolation bandwidth and 40-dB isolation FBW show a frequency width and fractional bandwidth with isolation characteristics above 40 dB. The proposed DB-BPF has both the features of compact size and good isolation. The size of the proposed DB-BPF could become more compact by improving the layout. Those advantages are obtained by the two proposed types of dual-band *LC* inverters with circuit structures composed of chip and patterned lumped elements.

7. Conclusion

A compact dual-band bandpass filter (DB-BPF) using chip and patterned lumped elements was realized. This was thanks to the two types of proposed dual-band *LC* *J*-inverters. Also, a large amount of attenuation between two BPF characteristics was realized by the effects of the proposed dual-band *LC* *J*-inverters. Although it was necessary to remove the effects of lumped element tolerances and to re-design the layout, a compact DB-BPF with a good frequency characteristic was realized.

Acknowledgments

This work is partly supported by the VLSI Design and Education Center (VDEC) at the University of Tokyo in collaboration with Keysight Technologies Japan, Ltd.

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